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Raising crop productivity of smallholder farmers in Sub-Saharan Africa: Long-term Ugandan fertilizer study

Innocent Muhereza[1]*, Deborah Pritchard[2,3] and David Collins[4]

[1]Sustainable Rural Enterprise Development Initiative (SREDI), Cooperative Building Plot 47/49 Nkrumah Road, Kampala, Uganda.
[2]Department of Agriculture and Environment, Curtin University, Bentley, Perth, Western, Australia.
[3]Agrieros Consulting, Glen Forrest, Australia.
[4]Boolar Boornap Nursery, Noongar Land Enterprise, Northam, Western Australia.

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Peri-urban small-holder farms throughout Sub-Saharan Africa (SSA) are predominantly run by women who traditionally use livestock manure as a fertiliser. The rates applied are often inadequate for optimum crop yields contributing to low farmer income and exacerbating food insecurity in the region. This report summarises targeted fertilizer experiments in Uganda from 2010 to 2019 aimed to improve crop yield. Preliminary soil testing in areas of Wakiso and Kampala indicated that nitrogen (N) was the most limiting macro-nutrient and thus the study design initially focused on increasing N, using animal manure, inorganic N fertilizer and/or N fixation using legumes. Plant yields increased by all sources of N although subsequent soil testing revealed issues with acidity, calcium (Ca) and magnesium (Mg)... The study had a strong emphasis on farmer empowerment by involving over 100 farmers and based on training received, farmers then established their own trials with positive yields obtained to lime ($CaCO_3$) and/or Epson salts ($MgSO_4$) in combination with N. The findings highlight the benefits of educating farmers in best nutrient practice as it resulted in higher crop yield and household income and has wider application for peri-urban farmers throughout SSA.

Key words: Peri-urban landholder, cattle manure, nitrogen fertilizer, soil acidity, crop yield.

INTRODUCTION

Declining soil fertility caused by minimal nutrient replacement has created a negative nutrient imbalance throughout much of Sub-Saharan Africa (SSA) (Vitousek et al., 2009; Chianu et al., *2012*). A shortage of research-based solutions and farmer implementation for smallholder farmers in these regions has additionally contributed to low crop yields (Kanonge et al., 2009; Adekunle et al., 2017). Fertilizer use in SSA accounts for slightly less than 2% of the world total with average application rates of 9 kg ha^{-1} being approximately 5 and 20% of that used in East Asia and Latin America, respectively (Jayne et al., 2003; Cedrez et al., 2020).

*Corresponding author. Email: muherezaa@gmail.com

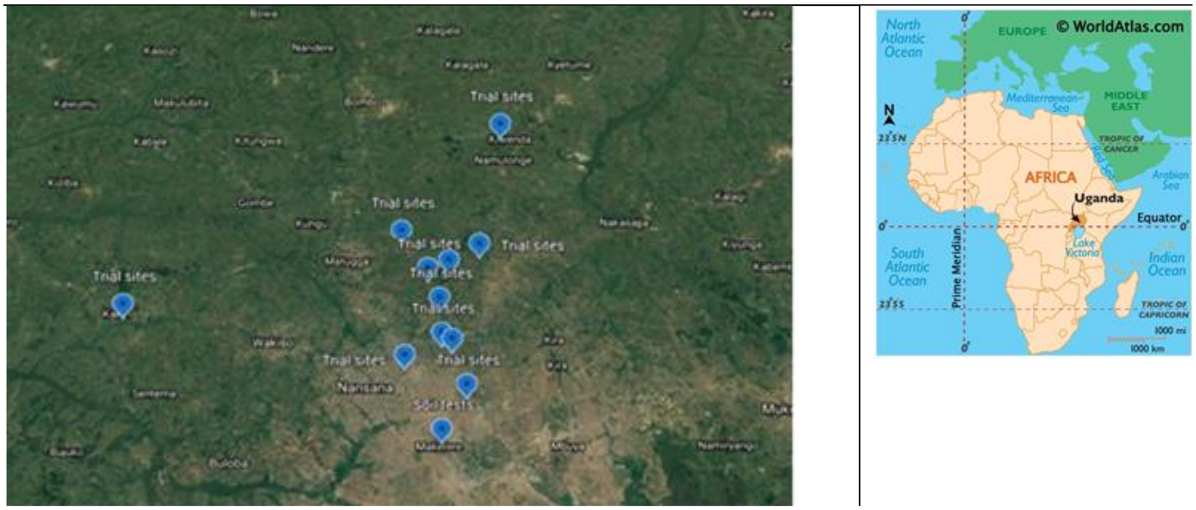

Figure 1. Location of each of the trial sites located in Wakiso and Kampala, Uganda. (Google maps, WorldAtlas.com).
Source: Google maps, WorldAtlas.com

Fertilizer use across SSA differs across the regions, with Uganda in particular, having extremely low relative fertilizer application rates of less than 1 kg ha^{-1} (Kaizzi et al., 2017). Traditionally it has been common to fertilize using animal manure. Inorganic fertilizer being often difficult to source and is of dubious quality (Omonona et al., 2014). In the central districts of Wakiso and Kampala in Uganda the majority (75%) of farmers are women on small holdings of between (0.2 - 0.8 ha) with inorganic fertilizer rarely used in these peri-urban regions. Only 55% of farmers source cattle manure but cannot fertilize the whole farm in a single cropping season due to lack of supply or affordability (Muhereza, 2010). In addition, the nutrient value of cattle manure is often wasted as most SSA countries do not focus on manure management in their practices (Ndambi et al., 2019). There is an urgent need to improve the nutrient balance of soils in these regions.

Fertilizer demand in SSA is forecast to expand at an average of 8% per annum and make this region the world's fastest growing fertilizer market. Sustainable research-based solutions that improve food security and improve economic development are urgently needed in these regions to reduce poverty and end hunger and malnutrition. Farmers often lack the education or training to identify constraints affecting crop production (Zake et al., 2005; Makivaro et al., 2017).

There are few studies in Uganda that have tracked the long-term effects of change in fertilizer practice and adoption by peri-urban farmers.

This research aimed to investigate the crop yield response to the application of various soil amendments such as inorganic N fertilizer, organic N from manure, lime, magnesium sulphate and inoculated legumes. The research doubled as a training platform to demonstrate to peri-urban farmers how to establish their own trials, improve crop yields producing a surplus that provided household income and improved dietary outcomes.

MATERIALS AND METHODS

Experimental design

A total of seven experiments were conducted between 2012 and 2019 in the peri urban districts of Wakiso and Kampala, central Uganda, which included 12 field sites with locations shown in Figure 1. There were at least two trials established at each site.

A summary of the key experiments conducted for each of the years (2012, 2015, 2017 and 2019), site location, treatments, rates and crops involved is given in Table 1. Nitrogen deficiency was identified by Muhereza (2010) as being the major soil constraint in the area and formed the initial design. Treatments were based on combinations and rates of either organic or inornaic nitrogen (N). Lime ($CaCO_3$) was also included in some treatments as soil pH testing over sites selected for the experiment indicated signs of soil acidity. Subsequent soil testing in this region during 2015 indicated that magnesium (Mg) and calcium (Ca) were also limiting elements and hence were investigated in 2017. An observation of over the long-term study highlighted that most farmers had low adoption of legumes in the crop rotation and therefore in the final year, the addition of correct rhizobia to enhance legume fixation was investigated to study improvements in legume grain yield.

Nitrogen fertilizer was applied in the forms of either inorganic N (urea) or organic N (locally sourced cattle or chicken manure). The N content of the various manures ranged from 0.5 to 2% N, depending on age and storage conditions, whereas the N content of urea was 46%. The highest rate of N was equivalent to a maximum of 100 kg N/ ha. A study on the effect of correctly inoculated bean legumes (*Phaseolus vulgaris*) as a more sustainable source of N formed a latter experiment. Two varieties of common bean (*Phaseolus vulgaris*) were sourced from a local seed supplier in Kampala. Freeze dried rhizobia suitable for common bean was provided by the Centre for Rhizobium Studies, Murdoch University Australia. The ameliorant lime ($CaCO_3$) to correct soil acidity was

Table 1. Summary of the seven experiments conducted for each of the years (2012, 2015, 2017 and 2019), location, the key treatments (nitrogen, lime, and magnesium sulphate and rhizobium inoculum), rates and crops involved.

Experiment	Year	Location	Treatment	Rate	Crop	Comments
1	2012	Namere Kyebando Kulika Nangabo	Nitrogen	Six treatments comprising: urea (20 g/m^2), urea (10 g/m^2), cattle manure (2 kg/m^2), cattle manure (1 kg/m^2), urea (10 g/m^2) + cattle manure (0.5 kg/m^2) and nil treatment	Dodo (*Amaranthus spp.*)	Nitrogen rates equivalent to 100 kg N/ ha at top rates of either cattle manure or urea.
2	2012	Namere Kyebando Kulika Nangabo	Lime x Nitrogen	Two treatments comprising: lime (1 kg/m^2) and nil lime for each of Experiment 1	Dodo (*Amaranthus spp.*)	Lime rate equivalent to 10,000 kg/ha (1 t/ha).
3	2015	Namere Nakanaku Nangabo Kitegombwa Kiti	Nitrogen	Four treatments comprising: urea (20 g/m^2), manure (2 kg/m^2), urea (10 g/m^2) + cattle manure (1 kg/m^2) and nil treatment	Chard (*Beta vulgaris*) African Cabbage (*Cleome gynandra*) Dodo (*Amaranthus ssp*)	Chard trials established with seedlings. The remainder established by direct seeding.
4	2015	Namere Nakanaku Nangabo Kitegombwa Kiti	Lime x Nitrogen	Two treatments comprising: lime (1 kg/m^2) and nil lime for each of Experiment 3	Chard (*Beta vulgaris*) African Cabbage (*Cleome gynandra*) Dodo (*Amaranthus ssp*)	Lime rate equivalent to 10,000 kg/ha.
5	2017	Namere Kulika Tula Kawempe Namere 2	Nitrogen x Magnesium Sulphate	Five treatments comprising; Nil, Urea 20 g/m^2, Urea 20 g/m^2 +$MgSO_4$ 20 g/m^2, Urea 10 g/m^2, Urea 10 g/m^2 +$MgSO_4$ 20 g/m^2		Epsom salts $MgSO_4$ was the only source of Mg available.
6	2017	Namere Kulika Tula Kawempe Namere 2	Lime x Nitrogen x Magnesium Sulphate	Two treatments comprising: lime (1 kg/m^2) and nil lime for each Experiment 5		
7	2019	Namere Luggungudde Kawempe	Nitrogen x Legume inoculation 12 sites	Treatments comprising two locally available common bean varieties, NAB 15 and NAB 20	Common bean (*Phaseolus vulgaris*)	Yield response to inoculation.

Source: Author

applied as a powder form sourced from a local Kampala supplier with purity of 92% ($CaCO_3$) as tested by Makerere University, Kampala. Epsom Salt ($MgSO_4$) was the only source of Mg in Uganda available to study, hence sulphur (S) was inadvertently applied in addition to Mg, although is considered in the results. For each experiment a randomized block design was used, and each treatment was replicated twice.

Site preparation, plot size and seed planting

All plots measured 1m x 1m and were marked out clearly by wooden markers. There was a 5 cm buffer between each plot to minimise the edge effect between plots. All treatments were arranged in a randomised block design and replicated twice. Plots were cultivated and levelled by hand with a hoe prior to treatments being applied and planting.

In 2012, the urea, cattle manure and/or lime treatments were applied at rates specified in Table 1 to each respective plot. Cattle manure was weighed manually in buckets, as was lime. For urea, an accurate weight by volume using an electronic balance was determined. All treatments were then spread by hand and all plots manually raked after treatments were applied. Dodo (*Amaranthus* spp) seed was pre-weighed for each plot (10 g) and on the day of sowing was mixed with a handful of sand and then broadcast evenly over each plot and lightly raked in.

In 2015, the urea, cattle manure and/or lime treatments were applied at rates specified in Table 1 and applied as per the 2012 experiment. Pre-germinated seedlings of chard (*Beta vulgaris*) or African cabbage (*Cleome gynandra*) were transplanted in equal numbers six to each plot in individual trials, depending on the site.

In 2017, the urea, cattle manure and/or lime treatments were applied at rates specified in Table 1 and applied as per the 2012 and 2015 experiment. The Mg treatment was applied by mixing the required quantity of Epsom Salt (MgSO4) with 1 L of water and applied with a watering can to the respective plots. Non Mg treatments were watered with 1 L of water only. Lime treatments were applied by hand on the respective plots and then raked in. To ensure an even coverage seed of Amaranthus, it was weighed for each plot (10g), mixed with sand and hand broadcast evenly over each plot and then lightly raked in.

In 2019, common bean (*Phaseolus vulgaris*) seeds (30 per plot) were used to examine the yield response to inoculation with a species of specific rhizobium compared to uninoculated (district practise) seed. There were a total of five rows in each plot. The rows were sown on the contour to reduce water running between

Table 2. Mean cumulative fresh matter yield (g m^{-2}) of dodo from three harvests at four sites in 2012 in response to various cattle manure (CM) and inorganic fertiliser (IF) treatments at rates up to 100 kg N/ha.

Treatment	Cummulative Yield (g m^{-2})				
	Namere	Kyebando	Kulika	Nangabo	Mean
Nil	1.650	1.510	1.440	1.290	1.472
CM (50%)	2.570	2.320	2.100	2.005	2.249
CM (100%)	3.040	2.923	2.760	2.651	2.844
IF (100%)	5.800	5.419	5.307	4.967	5.373
CM (50%) + IF (50%)	4.900	4.739	4.017	3.828	4.371

CM (50%) = cattle manure at 50% rate, NA = nil application, CM+IF (50%) = cattle manure (50%) and inorganic fertiliser (50%) rate, IF (100%) = inorganic fertiliser at 100% rate. The yield is the cumulative total of three consecutive harvests over three months
Source: Author.

plots during the growing season. The rhizobium inoculant was prepared for each plot by mixing the recommended amount of dry inoculant with 1 L of water. The inoculant slurry was poured over the rows of seed after planting and then lightly covered with soil by rake. The same volume of water was also applied to each of the nil treatments prior to the inoculant treatments to prevent cross contamination.

In all years, farmers tended the sites with any weeds removed by hand. No additional fertiliser or amendments were applied.

Harvest and statistical analysis

Harvest yields were recorded for each plot at each site after the plants reached harvest height. In 2012 and 2015 the number of dodo stems was counted for each plot and fresh matter (FM) was calculated on average of 12 of stems per bundle then weight per bundle. Three harvest cuts were taken over a three month period and a cumulative total calculated. Values were then converted to g m^{-2}. In 2017 FM yields were recorded and values were then converted to g m^{-2}. In 2019 grain yield of common beans after removing pods at ripening was recorded for each plot in g m^{-2}. All plant yield data (FM and grain yield) for all years was analysed by ANOVA in Microsoft Excel at the 99% level of significance.

RESULTS AND DISCUSSION

2012 Nitrogen field experiments

Plant yields

Table 2 presents the mean fresh matter (FM) yield of dodo in response to N application as either cattle manure and/or inorganic fertilizer treatment combinations over the four sites. All fertilizer treatments up to a maximum of 100 kg N/ha improved yield above the control at all sites. The FM yield of dodo under cattle manure at 100 kg N/ ha, were lower compared to inorganic fertilizer at equivalent rates of N.

The mean FM yield of dodo to inorganic N, combination of inorganic N plus organic N, and organic N for all sites (Namere, Kyebando, Kulika and Nangabo) are shown in Figure 2. All sites showed a similar response to the range of fertilizer treatments with dodo yields (g m^{-2}) under inorganic N (100 kg ha^{-1}) significantly higher ($P<0.01$) than equivalent total N provided solely by cattle manure. Inorganic N was more readily available to the crop compared to organic N in the short term as would be expected due to the slower and variable mineralization of N in cattle manure. In the longer term however, N from cattle manure may provide further benefits to the following crop more-so than inorganic N. Overall, the experiment highlighted that N deficiency was prevalent across the four sites with percentage relative yield above the nil N treatment ranging from 153% in the half rate of cattle manure (50 kg N ha^{-1}) to 366% in the inorganic N treatment (100 kg N ha^{-1}) (Table 3).

2015 Nitrogen + Lime experiments

Plant yields

Figure 3 presents the FM yield of plants as a response to various N fertilizer and lime treatments over 4 sites. The application of manure and urea plus lime significantly increased crop yields compared to the control treatment (NL) (Figure 3). Higher crop yields were obtained from urea treated plots with and without lime compared to manure treated plots. The trial at Namere had the highest yield followed by Kyebando, Kulika and Nangabo. Table 4 presents the 2015 soil test results. The soil sampled from three of four sites contained low levels of N which confirmed the extent of the deficiency over the sites. The fourth site was a heavier clay soil that had retained a moderate N content.

Due to past volcanic activity, the phosphorus (P) and potassium (K) levels were high or moderate and hence unlikely to have a response to these fertilisers. Calcium (Ca) was moderate at Kulika site and low at all other sites. Magnesium (Mg) was variable across the sites; medium to high in the sample from Namere, medium in sample from Tula Kawempe and low at Kulika and Namere II.

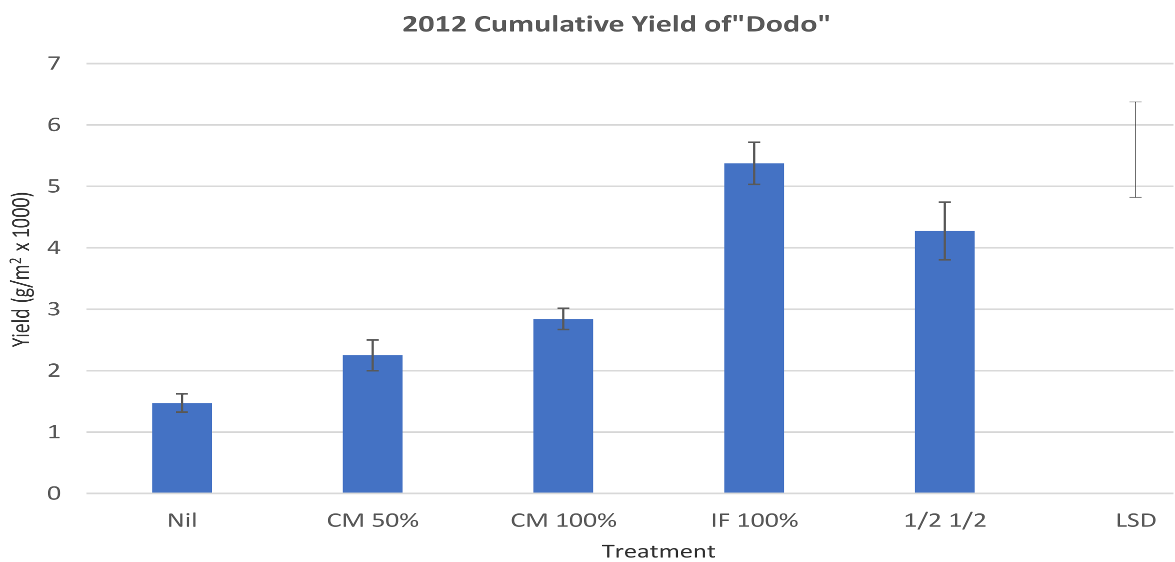

Figure 2. Mean dodo fresh matter yield (g m^{-1}) from three consecutive harvests taken at maturity averaged across the four sites (Namere, Kyebando, Kulika and Nangabo). CM (50%) = cattle manure at 50% rate, NA = nil application, CM+IF (50%) = cattle manure (50%) and inorganic fertiliser (50%) rate, IF (100%) = inorganic fertiliser at 100% rate. ½ ½= CM (50%) + IF (50%) LSD (P<0.01).
Source: Author.

Table 3. Percentage relative increase of dodo yield in 2012 compared to the nil treatment.

Treatment	Nil	CM 50%	CM 100%	IF 100%	CM 50% IF 50%
Relative yield	100	153.1	267.4	366.0	290.5

Source: Author.

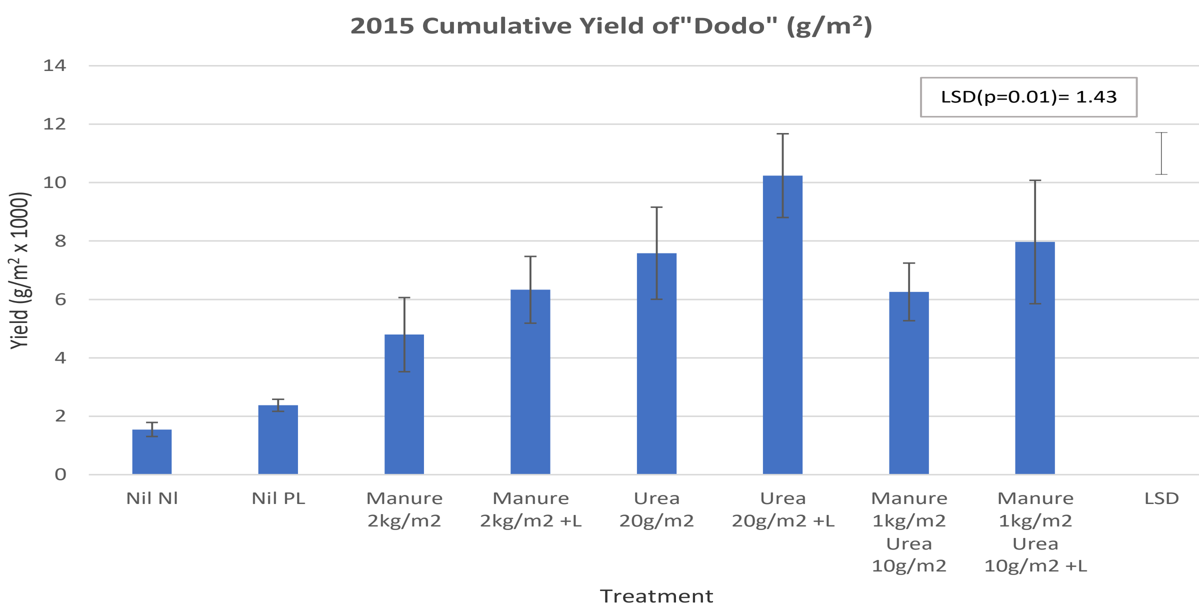

Figure 3. Mean fresh matter yield (g m^{-2}) of leafy green species Chard, African Cabbage and Dodo as a response to various nitrogen fertiliser and lime treatments over 4 sites in 2015 (n=2). At four sites in Namere, Kyebando, Kulika and Nangabo. NL = No Lime, PL = plus Lime**.**
Source: Author.

Table 4. Levels of available nutrients (mg/kg^{-1}) of nitrogen, phosphorus, potassium, calcium and magnesium measured at four sites in 2015 as indicated by the La Motte soil testing kit.

Nutrient					
References (mg kg^{-1})	**Nitrogen (mg kg^{-1})**	**Phosphorus (mg kg^{-1})**	**Potassium (mg kg^{-1})**	**Calcium (mg kg^{-1})**	**Magnesium* (mg kg^{-1})**
Site					
Namere	Low (5)	High (50)	Moderate (50)	Low (150)	Medium to high
Kulika	Low (5)	High (100)	High (150)	Moderate (2800)	Low
Tula Kawempe	Low (5)	High (100)	High (200)	Low (350)	Medium
Namere II	High (75)	High (100)	High (200)	Low (350)	Low
	La Motte soil test kit standard range				
References (mg kg^{-1})	**Nitrogen (mg kg^{-1})**	**Phosphorus (mg kg^{-1})**	**Potassium (mg kg^{-1})**	**Calcium (mg kg^{-1})**	**Magnesium* (mg kg^{-1})**
Low	<15	<10	<50	<500	-
Moderate	15-30	10-17	50-70	>1000	-
High	>30	>17	>70	>5000	-

*Mg estimated by colour grade
Source: Collins (2012).

According to World Classification, these soils are classified as Ferralic Nitisol (Krasnozems) (Mckenzie and Gallant, 2006; FAO, 2015). They are free draining and non-hydrophobic soil with high cation exchange capacity due to the high percentages of clay and silt. Luggungudde, Tula Kawempe, and Namere in particular, had low Ca levels. Overall, farmers were advised whether to add N fertiliser, lime or MG where soil tests indicated a likely or possible response.

Nitrogen was shown to be the main limiting nutrient in the majority of sites, followed by Mg and Ca. The tests indicated the majority of sites were adequate in P and K (Table 5). Figure 4 shows the colour of soil and sample taken.

2017 experiments

Figure 5 presents the yield response of crops to urea, magnesium sulphate and lime that were established in both Kampala and Wakiso districts in 2017. There was a linear increase in crop yield as a response to urea and admixture of urea and magnesium sulphate with lime. The highest crop yield was recorded in urea 20 g/m^2 + $MgSO_4$ 20 g/m2 with lime, followed by urea 20 g/ha plus $MgSO_4$ Nil lime followed by urea 20 g plus lime and urea 20 g No lime, compared to nil as a baseline yield. 10 g Urea/m^2 = 4.6 g N m^{-2} (46 kg N/ha); 20 g Mg SO_4 /m^2= 9.8% Mg (19.6 kg Mg/ha) and 13% S (26 kg S/ha).

Table 6 shows the percentage relative increase in yield compared to the nil treatment and highlights that a 662% improvement in yield was possible using a balanced mix of urea, magnesium sulfate and lime.

2019 experiments

Figure 6 shows the yield of two common bean varieties (NAB 20 and NAB 15) was increased significantly as a response to inoculation by species specific rhizobia. These values converted from dry bean yields of 780 kg/ha^{-1} (uninoculated) to 1300 kg/ha (inoculated).

It is well documented that correct legume inoculation improves yield (Rurangwa et al., 2018; Wolde-meskel et al., 2018; Belete et al., 2019) (Collins) but there was limited uptake of this knowledge in the study areas examined. Legumes are difficult or expensive to purchase and because of lack of rhizobium the yields were low. The use of legumes in crop rotation in Uganda has declined over recent years with preference given to staple cash crops, such as maize (*Zea mays* L) to feed the increasing peri-urban population. The experiment showed that high yields of legumes were possible using inoculated seeds with the correct rhizobia. This resulted in providing more legumes for family consumption, which are a high protein food source as well as seed for cash sales.

Figure 4. Soil colour and samples taken.
Source: Author.

Table 5. 2015 Percentage relative increase in yield as a response to various rates of urea and manure compared to the Nil treatment **(all m2).**

Treatment	Nil	Nil + L	Urea 20 g	Urea 20 g + L	Manure 2 kg	Manure 2 kg + L	Manure 1 kg Urea 10 g	Manure 1 kg Urea 10 g + L
% Relative Yield	**100**	154	489	661	310	408	404	514

Lime applied at 1 kg/ m^{-2}.
Source: Author.

Table 6. 2017 Percentage relative increase in yield compared to the nil treatment.

Treatment	Nil	Nil PL	Urea 10 g	Urea 10 g PL	Urea 10 g + $MgSO_4$ 20 g	Urea 10 g + $MgSO_4$ 20 g PL	Urea 20 g	Urea 20 g PL	Urea 20 g+ $MgSO_4$ 20 g	Urea 20 g +$MgSO_4$ 20 g PL
% Yield	100	92.3	183	194	254	333	391	393	503	662

Source: Author.

Overall highlights and challenges

The study highlighted the extent of nutrient deficiency in Uganda in the sites examined likelihood of soils to respond to application of N, lime (for raising pH and Ca) and Mg. A total of 54% of sites were likely to respond positively to N fertilizer, 25 % to liming to ameliorate acidity, 28% to calcium and 17% to magnesium. Table 7 shows the percentage of sites within the project area likely to respond to fertilizer treatment. In this study, small landholders predominately women

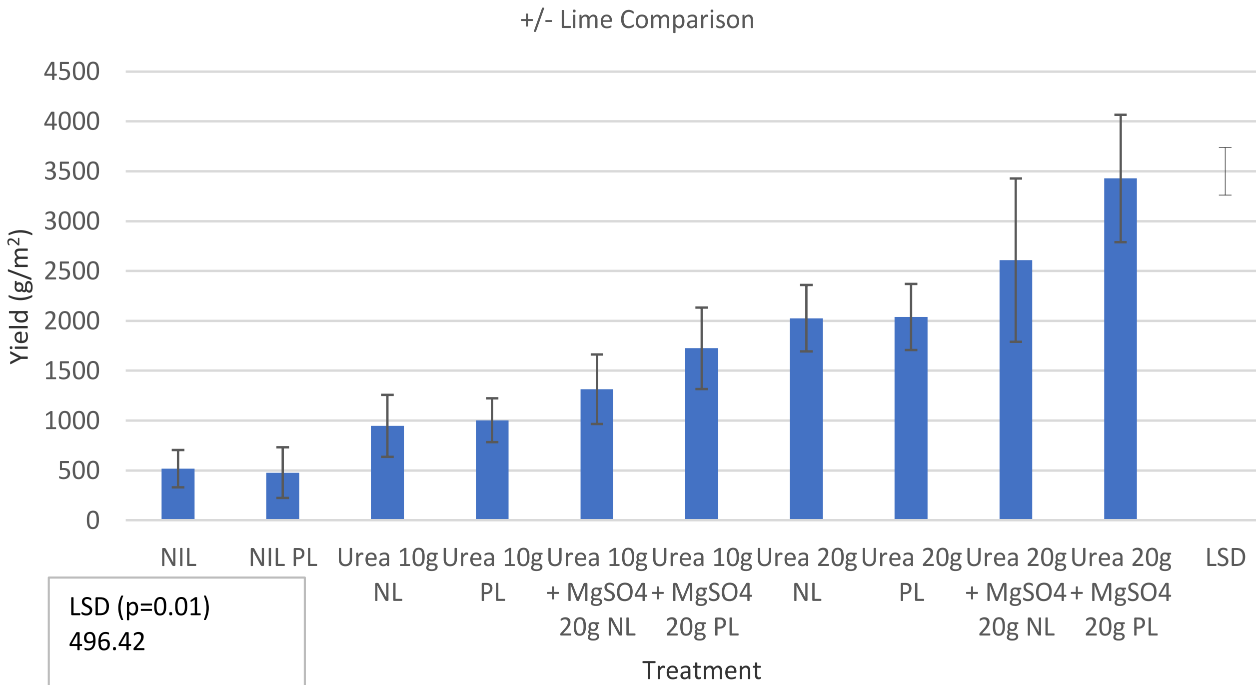

Figure 5. FM yield as a response to application of Urea and Magnesium Sulphate with and without lime. PL = plus lime, NL = no lime. Lime applied at 1 kg/m^2.
Source: Author.

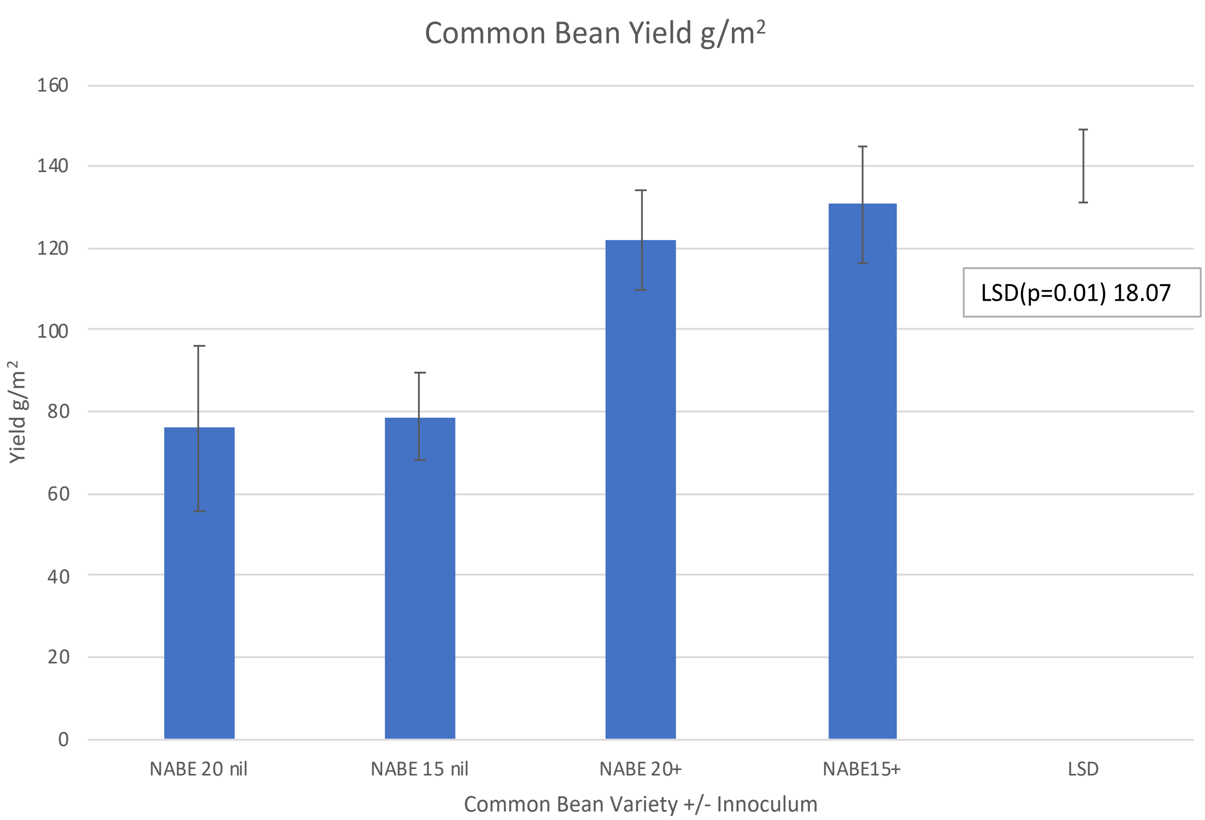

Figure 6. Yield of two common bean varieties (NAB 20 and NAB 15) as a response to inoculation by species specific rhizobia.
Source: Author.

Table 7. Percentage of sites within the project area likely to respond to fertiliser treatment (n= 30).

Soil parameter	Likely to respond to treatment (%)	Possible response to treatment (%)	Adequate unlikely response (%)
Nitrogen (N)	54	10	36
Phosphorus (P)	7	7	86
Potassium (K)	0	17	83
Magnesium (Mg)	17	14	69
Calcium (Ca)	28	25	47
Acidity (pH)	25	14	61

Source: Author.

(75%) were empowered with the skills and confidence to allocate their limited resources more efficiently using hands-on training activities such as designing a small field trial, data collection, measuring and recording crop yield.

All trials were based on current soil and plant testing data helping to address longer term decline in soil fertility.

There is an urgent need in Uganda for farmer training and education incorporating the assessment of soil fertility through plant and soil nutrient testing. The most efficient fertilizer application rates to improve crop yields needs to be determined, including improved inoculation of legumes in crop rotation as an alternative source of N, improved storage of cattle manure to preserve nutrients, sourcing effective amendments to ameliorate soil acidity, the importance of macro- nutrients and their importance to plant growth, and identifying other essential micro-nutrients. The final field experiment included the use of legumes in the crop rotation to boost soil N status. Legumes also have the added benefits of a disease break for following crops, benefits of rhizobia bacteria, assessing the health and effectiveness of rhizobia root nodules and are important in the diet for human health.

Organizations in Africa such as the IFPRI emphasize the importance of research-based solutions that contribute to food systems transformation in line with development to sustainably reduce poverty and end hunger and malnutrition.

The small field trials established with this program have demonstrated firsthand to landholders' that increased yields are possible with adequate nutrient supply and soil amelioration.

Conclusion

This long-term experiment in Uganda has demonstrated that agricultural productivity and crop growth is possible where focus is given to improving soil nutrition. Yield increases of up to 600% above district practice were possible with the application of adequate rates of nitrogen combined with lime and magnesium sulphate. The benefits of improved rhizobium to inoculate legumes to increase their grain yield were established in this experiment. There is further scope to test a wider range of nutrients and combinations, not covered by this research. Much value could be gained by educating and including farmers to speed up the adoption of optimum fertilizer application to promote yield and food security in Uganda and SSA.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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